
VOLUME 46, ISSUE 8, OCTOBER 2008
ISSN: 0925-7535
ELSEVIER
safety science
Available online at
ScienceDirect
www.sciencedirect.com

Available online at www.sciencedirect.com

ScienceDirect

Safety Science 46 (2008) 1223–1233

SAFETY SCIENCE

www.elsevier.com/locate/ssci

Tinted windshield and its effects on aging drivers' visual acuity and glare response

Wen Shi [a], Thurmon E. Lockhart [a,*], Mehran Arbab [b]

[a] *Grado Department of Industrial and Systems Engineering, Virginia Polytechnic Institute and State University, 250 Durham Hall, Blacksburg, VA 24061, USA*

[b] *PPG Industries, Inc., Pittsburgh, PA 15238, USA*

Received 19 December 2006; received in revised form 31 March 2007; accepted 3 August 2007

Abstract

Increasingly, automobile designers are utilizing tinted glasses for concept cars, specialty models, or to differentiate their vehicles. The objective of this study was to assess whether alternating different tinted windshields would affect aging drivers' visual acuity and glare response. Two commercially available windshields (bluish and greenish with same transmittance) were compared. The tests of visual acuity, contrast threshold, glare detection, and discomfort glare rating were performed to address the windshield effects on both the older and younger populations. Fourteen elderly and seven young individuals participated in the study. The results indicated that alternating between the tested tinted windshields would not affect drivers' visual performance for both age groups. The implications and future research are discussed.
Published by Elsevier Ltd.

Keywords: Tinted windshield; Aging; Visual acuity; Discomfort glare; Disability glare

1. Introduction

Many original equipment manufacturers (OEM's) today utilize tinted glass for solar heat load reduction and to differentiate their vehicles. Both of these goals, heat load reduction in particular, will benefit from an overall reduced transmittance, i.e. darker glass. The US federal regulations on coloring or tinting windshields (the front window in a vehicle, also called windscreen) elaborate that "coloring or tinting of windshields is allowed, provided the parallel luminous transmittance through the colored or tinted glazing is not less than 70% of the light" (US Federal Motor Carrier Safety Administration, DOT, 49 CFR 393.60). Other national or regional regulations in the US may require a higher level of visible transmittance, i.e. 75%, for vehicle windshields. Therefore, the glass manufacturer designs the glass composition or coated glass to approach, but not go below the required transmittance limit for most windshield configurations. However, even at similar total visible transmittance, the spectral distribution of light will be different after passing

---

[*] Corresponding author. Tel.: +1 540 231 9088; fax: +1 540 231 3322.
E-mail address: lockhart@vt.edu (T.E. Lockhart).

0925-7535/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.ssci.2007.08.001

through a tinted glass (Long and Garvey, 1988). As a result, windshields of different colors will bring lights of different spectral contents to the driver and thus may change his or her visual performance. Additionally, previous studies indicate that one's visual performance such as visual acuity and contrast sensitivity diminishes with aging (Ginsburg, 1986), and elderly drivers suffer from headlight glare (Lockhart et al., 2006; Siew et al., 1981) from approaching vehicles. As such, the change of windshield's color is likely to influence older drivers differently from younger drivers. Therefore, a study was designed to address whether altering different tinted windshields would affect drivers' visual performance and whether older drivers were influenced to a different extent. For this purpose, the effects of tinted windshields on the visual performance of people at different ages were evaluated by testing their visual acuity and glare response, both of which are critical to driving a vehicle safely and potentially affected by windshield tinting.

Visual acuity is the ability of the eye to perceive spatial details at a given distance, and is an important indicator of human vision. Studies suggest that visual acuity is an important component of driving, and the decline of visual acuity is likely to affect complex driving tasks (Shinar and Schieber, 1991). In general, visual acuity is affected by aging and the spectral distribution of the light reaching the eye. Visual acuity begins to decline from the normal level around 40–50 years of age (Owsley and Sloane, 1990) and continues to decline throughout the rest of life (Weymough, 1928). The age-related degradation of visual acuity stems mainly from the weakening of the elasticity of the crystalline lens that degrades the accommodation process. With the decrease of the accommodative ability, older adults cannot focus on near images effectively, resulting in presbyopia and the decline of visual acuity. Prior research suggests that the age-related accommodation loss can be optimized when utilizing a target wavelength of blue color spectrum (Long and Garvey, 1988). In other words, the accommodation is most accurate and the oculomotor adaptation is minimal at this region of color spectrum. As a result, the change of different tinted windshields may play a role in drivers' visual acuity, especially older drivers', if this change alters the blue color spectrum of the light after passing through the windshields.

On the other hand, the visual performance associated with the onset of glare light, i.e. glare response, may also be influenced by tinted windshields. "Glare is produced by brightness within the field of vision that is sufficiently greater than the luminance to which the eyes are adapted so as to cause annoyance, discomfort, or loss in visual performance and visibility" (the 1984 reference volume of the Illuminating Engineering Society of North America). Generally, the effect can be expected to be momentary and to disappear after either the removal of the light source or adaptation of the eye to the new conditions. Glare effects are usually classified into disability glare and discomfort glare. Disability glare is defined as the reduction of visibility due to the scattering of light in the eye, while discomfort glare is the sensation of annoyance or pain that is felt in the presence of bright light. Studies have shown that the color spectrum of glare light does not change disability glare to a great extent, because disability glare is a foveal effect, where sources matched for photopic illuminance will produce similar effects (Van Derlofske et al., 2004). As for discomfort glare, on the other hand, it relates greatly to the spectral contents of the light source. Generally speaking, the more bluish color or higher correlated color temperature will lead to higher discomfort glare (McLaughlin et al., 2004; Sivak et al., 1994, 1997, 2003; Van Derlofske et al., 2004, 2005). The mechanism of this may be ascribed to Kerker's (1969) claim that the light scattering intensity is inversely related to the wavelength of the light source. Since the bluish light is of short wavelength and thus is more scattered, the feelings of discomfort may be more prevalent. Moreover, as glare effects get worse in aging individuals due to the increased scattering of the light with advanced age (Siew et al., 1981), higher discomfort may be perceived by older drivers if the light, after passing through a tinted windshield, has a greater amount of bluish spectrum contents. In this sense, with the consideration of the potential color spectrum effects on visual acuity (i.e. visual acuity may be improved by a light of blue color spectrum), mixed effects of the blue color spectrum may exist.

In summary, there is a reason to assume that the change of spectral contents by different tinted windshields may affect drivers' visual acuity and glare response (especially, discomfort glare). To elucidate this possibility, two commercially available windshields (PPG Industries, Inc.) were tested. That is, having the same transmittance (75%), a bluish windshield and a greenish windshield were used (the detailed description of the windshields is provided in the methods section). Visual acuity, contrast threshold, glare detection, and discomfort glare rating were assessed to evaluate the windshield effects on age-related visual performance. We hypothesized that alternating between the windshields would result in the change of the tested visual performance and older adults would be affected differently from younger counterparts. This study would have practical implications in automotive glass design, which would ultimately enhance drivers' comfort and safety. Understanding these critical factors would help focus our attention towards developing the most relevant and optimal automotive glass designs for both older and younger populations.

2. Methods

2.1. Subjects

Altogether, 21 subjects were tested. In the younger age group, seven subjects were tested (four males and three females) with an average age of 26 years (22–30 years), and the older age group consisted of 14 subjects (seven males and seven females) with an average age of 74 years (65–89 years). The participants were recruited from the general student population at Virginia Tech and the local community at Blacksburg, VA. All of the participants had a valid Virginia Driver's License and were screened assuring that each of them had at least corrected normal vision (20/20 measured by the Bausch & Lomb Vision Tester), normal contrast sensitivity curve (measured by the Vistech Contrast Test System), and no color vision deficits (measured by the Bausch & Lomb Vision Tester). Also, no participants reported having history of eye disease and no elderly subjects had cataract surgery or intraocular lens implantation. Before testing, each participant signed a consent form approved by the Institutional Review Board (IRB) at Virginia Tech and monetary compensation was provided for their effort.

2.2. Visual acuity session

2.2.1. Setup

The experiment was conducted in the Night Vision Laboratory at the Human Factors Engineering & Ergonomics Center, Virginia Tech. Fig. 1 illustrates the experimental setup. A bluish windshield (the CIE 1931 (x, y, Y) coordinates: 0.399, 0.417, 50 cd/m^2 measured by a Minolta CS-100 photometer for a 2° observer under the simulated daytime light similar to the illuminant D65) and a greenish windshield (the CIE 1931 (x, y, Y) coordinates: 0.415, 0.428, 51 cd/m^2 measured under the same conditions) were used. The distance from the windshields to the eye level of the subject was set at 60 cm and the mounting angle of the windshields was 40° from the horizontal, both of which were determined by measuring and averaging the windshield distance and angle from several vehicles. Under the daytime conditions, the light source was similar to the sunlight which set the ambient conditions at 700 lx, while in the nighttime conditions, most of the lights were

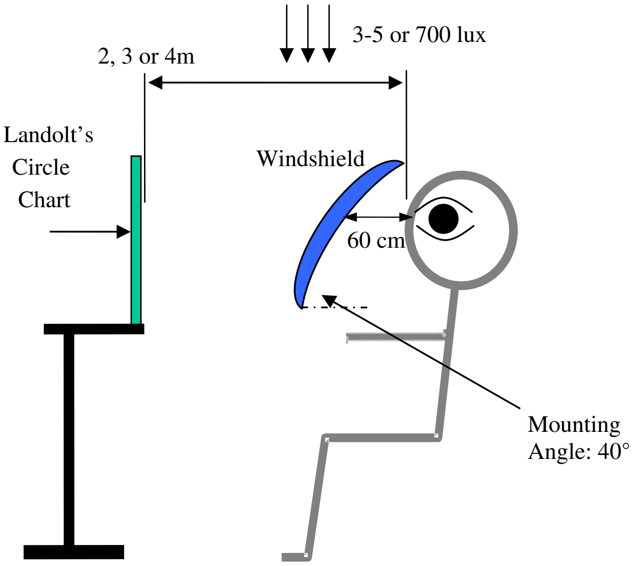

Fig. 1. The setup of the visual acuity session.

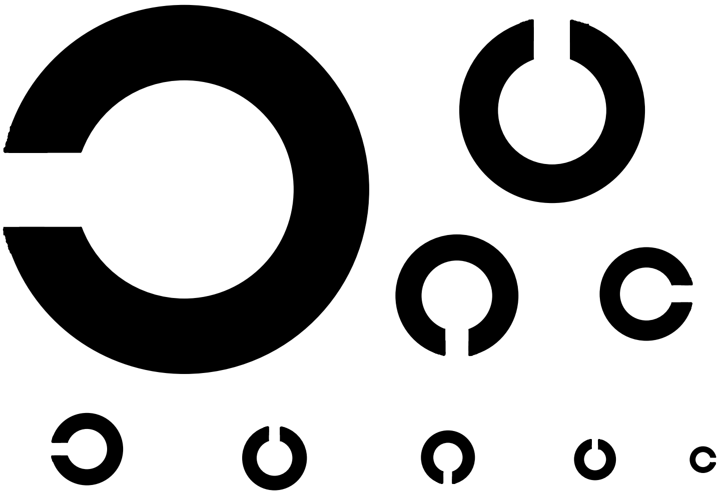

Fig. 2. The Landolt's circle chart.

turned off or down, leaving the ambient conditions at 3–5 lx. Each subject was asked to sit in a simplified vehicle equipped with the tested windshields (one at a time) and fix his or her eyes in the middle of the Landolt's circle chart (Fig. 2). In the daytime conditions, a Frezzi Super Sun Gun 200 with a Philips MSR 200 HR lamp was used to provide extra lighting, which has a color temperature close to the sunlight, i.e. 6000 K, and set the illuminance of the chart surface at 1000 lx. In the nighttime conditions, the Landolt's circle chart was displayed by a laptop, the luminance of whose screen was controlled at 4 cd/m^2 (Lockhart et al., 2006). Although using a laptop to display images may be a poor approximation of the quality of an image that is viewed when light is reflected from it, the setup of the experiment was regarded as cost-effective to assess one's visual performance at night (e.g. the visibility of a sign that is illuminated by backlight), as it would be hard to control the potential confounding effects caused by using extra lighting to illuminate an image at the nighttime conditions.

2.2.2. Procedure

The Landolt's circle chart was placed at 2, 3 or 4 m away from the subject's eyes, which simulated the normal range of the focus of the eyes when a driver looks forward in driving (Atsumi, 1995). At each distance, the subject was asked to tell the gap direction from the biggest circle to the smallest circle until s/he could not detect the difference. As shown in Fig. 2, the nine circles represented visual acuity (in visual angle) from 6.8 to 96.5 min of arc in the following nine steps: 6.8, 9.8, 13.7, 17.4, 19.0, 26.7, 43.2, 67.3, and 96.5 min. The sizes of the circles were adjusted for testing visual acuity at various distances. This session was conducted under both daytime and nighttime conditions for each of the windshields, and different Landolt's circle charts were used at each trial to eliminate the effects of memorization. Between the daytime test and the nighttime test, a 15 min dark adaptation was given to each subject.

2.3. Glare response session

2.3.1. Setup

Fig. 3 illustrates the setup of this experiment. The ambient conditions were set to the same nighttime conditions as in the preceding session. A high-intensity discharge (HID) headlamp was used as the glare source. Using the neutral density filters, the headlamp was able to output glare light at two illuminance levels. That is, in order to test both disability glare and discomfort glare, the glare illuminance levels at the eye level of each subject were selected at 6 lx and 20 lx, partially based on Theeuwes et al. (2002) study. The height of the headlamp aperture and the middle of the Landolt's circle target were set to the same level. The aperture of the headlamp was controlled at 0.75 cm and located 10 degrees away from the subject's line of sight to the left direction. This setting was designed to simulate the actual situation for an oncoming car at 50 m away. A Landolt's circle target displayed by a laptop was placed in line with the headlamp enclosure for all conditions.

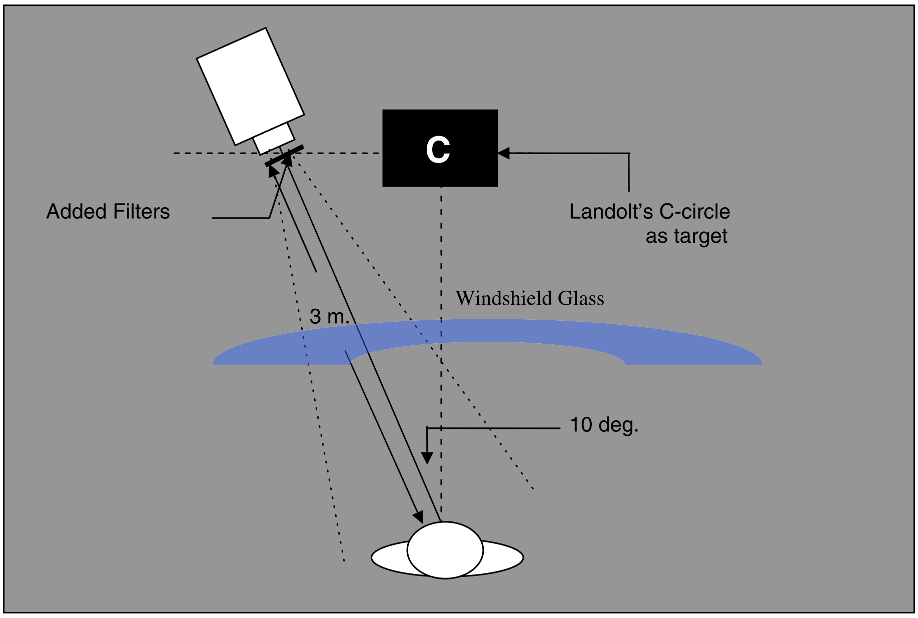

Fig. 3. The setup of the glare response session.

Each subject's eye level was also adjusted to align with the middle of the circle target. The size of the target was designed using LabVIEW 6.0 program based on the actual size of the circle for testing visual acuity at 20/200 or 0.1 at the test distance of 3 m with a visual angle of 96.5 min of arc. By using this system, the gap location of the circle target was changed randomly in the experiment (i.e. left, right, up, and down). The contrast level of the target displayed by the laptop screen was adjusted by changing the gray level of the background controlled by the software. That is, the default contrast level between the black Landolt's circle target and the background was 0 as the gray level of the background was 0, i.e. black. By increasing the gray level (i.e. the contrast level), the background became brighter and the black target appeared more salient and easier to detect. As the gray level ranged from 0 to 255 (i.e. black to white), the contrast level displayed had 256 levels, each of which was used to indicate the threshold of the visibility of the participant.

2.3.2. Procedure

First, each subject was asked to put his or her head on the chin rest, view through one of the windshields, and fix their eyes in the middle of the laptop screen. She/he was asked to feel the glare coming from the headlamp for 1 s and then rate the glare according to the revised DeBoer Discomfort Glare Rating Scale (Developed by the Human Factors Engineering & Ergonomics Center, Virginia Tech, and used by Virginia Tech Transportation Institute. See Appendix A for details). After reporting his or her rating and having a 1 min break, his or her visual contrast threshold was tested with and without the onset of the glare light. In this contrast threshold test, a Landolt circle target created by LabVIEW 6.0 was loaded on the laptop and it was possible to change its contrast and gap direction. The subject was asked to report his or her threshold of visibility by performing the "Ascending Trial" and the "Descending Trial". The protocol used in the "Ascending Trial" was: "On the screen, there will be a broken circle similar to the letter C in the middle of it. I will continually increase the image's contrast so that it becomes more detectable. At each increasing level, I will ask you to report whether you could detect the C target or not. If a 'yes' response is received, I will ask you to report the direction of the broken gap. The correct identification of the gap direction will stop the trial. However, if a 'no' response is received or the gap direction is incorrect, I will successively increase the contrast of the target to the next level". The similar protocol was used in the "Descending Trial". This entire process was repeated twice with two 1 min breaks, and the subject's contrast threshold was achieved by averaging the results of all of the trials. After this test, the headlamp was rotated toward the subject and s/he was instructed to inform the experimenter to stop the rotation at two moments. The first moment was when the subject began to perceive the glare light coming into their eyes, and the second moment was when glare was unbearable. The rotation of the headlamp was controlled by the experimenter at a constant speed of 8 degrees per second. In all, two glare levels were tested in each of the three tests and a counterbalance plan was made between the windshield types (bluish vs. greenish) and the glare levels (6 vs. 20 lx).

2.4. Data analysis

The raw contrast threshold data were no more than the contrast levels displayed by the laptop. The nighttime contrast threshold was obtained by converting these values into the Weber contrast ratio

$$\begin{aligned}&\text{Contrast Ratio} = (L_{\text{b}} - L_{\text{t}})/L_{\text{b}}\\&\text{where}: L_{\text{b}} = \text{Luminance of the background}\\&\qquad\quad L_{\text{t}} = \text{Luminance of the circle target}\end{aligned}$$

Both L_{b} and L_{t} were measured in cd/m^2 using a photometer (Minolta CS-100). Corresponding to each contrast level, a Weber contrast ratio was determined. The higher the contrast level was (i.e. worse visibility), the larger the Weber contrast ratio would be. In order to reduce the measurement errors in determining the Weber contrast ratios, a quadratic regression model ($R^2 = 0.99$) was fitted between contrast level (x) and Weber contrast ratio (y), and was used to predict Weber contrast ratios, which were used in data analysis, for all of the contrast levels collected in the experiment. Multiple-way ANOVA tests with $\alpha = 0.05$ were performed in JMP 5.1 to analyze the data collected in all of the tests. For the visual acuity session, the main effects included age, ambient condition, windshield type, and test distance. The dependent variable in this session was visual acuity. As for the glare response session, the dependent variables were discomfort glare rating, contrast threshold, and headlamp rotation angle, while the main effects tested for each of them were age, windshield type, and glare level. Except the age main effect (between-subjects), all of the main effects were within-subject effects. All of the interactions were included in the models.

3. Results

In general, no significant windshield color effects were found ($p > 0.05$) in any of the tests (i.e. the visual acuity test, the discomfort glare rating test, the contrast threshold test, and the glare detection test), indicating that the two tested windshields performed similarly in terms of the tested visual performances. Although the older subjects performed worse than the younger counterparts in most of the tests, there was no evidence showing that the tested windshields worked differently between the older and younger subjects. The detailed results of each test are as follow (since none of the interaction effects was of statistical significance ($p > 0.05$) in any of the tests, only the results of the main effects are reported).

3.1. Visual acuity

Significant age effects ($F_{1,228} = 10.5$, $p = 0.0014$) and ambient lighting condition effects ($F_{1,228} = 24.6$, $p < 0.001$) were found in the visual acuity test. Overall, the results indicated that the younger subjects had higher visual acuity (mean visual acuity across the distances = 8.3 min of arc with s.d. = 1.21) than the older subjects (mean visual acuity across the distances = 13.8 min of arc with s.d. = 2.73) at all distances (i.e. 2 m, 3 m, and 4 m), and visual acuity decreased from daytime conditions (mean visual acuity across the distances = 10.5 min of arc with s.d. = 1.87) to nighttime conditions (mean visual acuity across the distances = 16.3 min of arc with s.d. = 2.44) for all subjects at all distances. Similar to these results, Corso (1981) findings also suggest that visual acuity is improved when the overall illumination is increased for all ages. As for the windshield effects ($F_{1,228} = 0.4$, $p > 0.05$), the visual performance was similar across the age groups at all of the distances under each ambient lighting condition, indicating no significant difference attributable to the windshields. As mentioned previously, however, utilizing a target wavelength of blue color spectrum may improve one's visual acuity. At the same time, the chromaticity coordinates for the two windshields, i.e. ($x = 0.399$, $y = 0.417$, $Y = 50$ cd/m^2) for the bluish windshield vs. ($x = 0.415$, $y = 0.428$, $Y = 51$ cd/m^2) for the greenish windshield, suggested that at 75% visible light transmittance, both of the windshields should have sufficient intensity in the blue range of their color spectrum to preclude significant windshield effects. In addition, no significant distance effects ($F_{2,228} = 0.4$, $p > 0.05$) were found, indicating that the visual acuity of the subjects did not change within the test distance of 2–4 m under the current experimental setup.

3.2. Discomfort glare rating

For both age groups (Fig. 4), only the two glare levels (i.e. 6 lx and 20 lx) had statistically significant effects on discomfort glare rating ($F_{1,76} = 16.3$; $p = 0.0001$), indicating that high glare illuminance led to high discomfort (mean = 6.3; s.d. = 0.25 for 20 lx vs. mean = 5.4; s.d. = 0.24 for 6 lx). Although there was an apparent indication that the ratings for the glare light under the bluish windshield were higher (more uncomfortable) than those under the greenish windshield, no significant windshield effects ($F_{1,76} = 3.9$, $p > 0.05$) meant that the two tested windshields did not differ remarkably in terms of causing discomfort glare. In other words, similar feelings under the two windshields were perceived by the subjects in spite of the observation that the mean rating under the bluish windshield was slightly higher. Besides, the age effects were also not significant in this test ($F_{1,76} = 1.2$, $p > 0.05$). It was interesting to note, however, that the older subjects generally rated less (mean = 5.4, s.d. = 1.63) than the younger subjects (mean = 5.8, s.d. = 1.37), indicating that the elderly subjects reported less discomfort glare (Fig. 5). According to the literature, mixed findings were found about the age effects on discomfort glare rating (McLaughlin et al., 2004), that is older people in some studies reported less glare than the younger ones, but in some other studies higher discomfort glare ratings were found for the older group. The cause of reporting less glare may be due to the tendency of older people to use more favorable subjective ratings than younger people (McLaughlin et al., 2004).

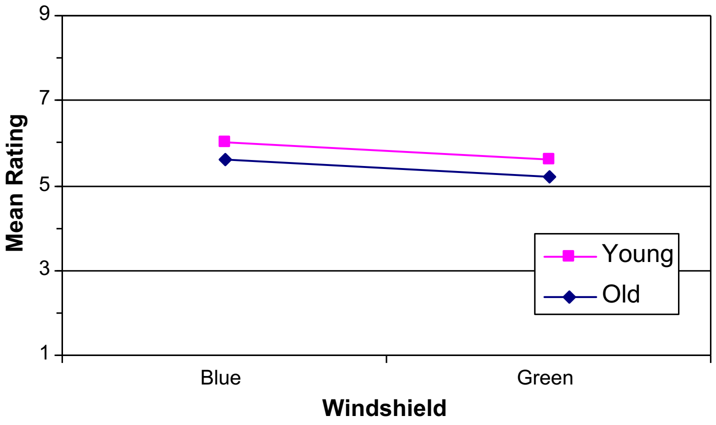

Fig. 4. Age * glass interaction on discomfort rating.

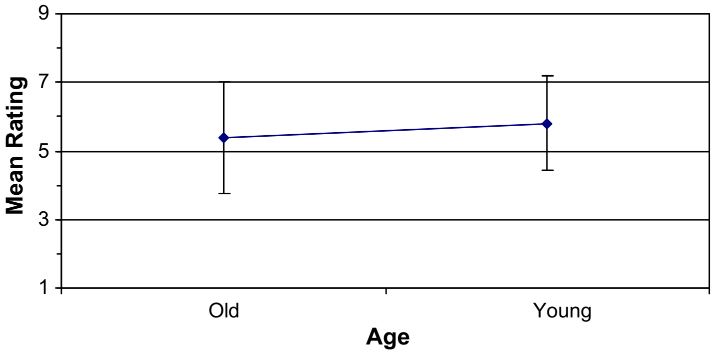

Fig. 5. Age main effect on discomfort rating.

3.3. Contrast threshold

Both the age effects and the glare effects were statistically significant ($F_{1,72} = 15.5$, $p = 0.0002$; $F_{1,72} = 48.4$, $p < 0.0001$, respectively), which indicated that the older subjects performed worse (mean contrast ratio for the older group = 0.14 with s.d. = 0.08 vs. mean contrast ratio for the younger group = 0.12 with s.d. = 0.10) and as the glare intensity increased, so did the contrast threshold (mean contrast ratio for the higher glare = 0.18 with s.d. = 0.07 vs. mean contrast ratio for the lower glare = 0.09 with s.d. = 0.06) (Abrahamsson and Sjostrand, 1986; Paulsson and Sjostrand, 1980). Again, there was no significant difference due to the windshields ($F_{1,72} = 1.1$, $p > 0.05$), indicating that the difference of the two windshields did not influence disability glare to a significant extent. Knowing that both of the glare illuminance levels (i.e. 6 lx and 20 lx) could trigger photopic vision, the findings agreed with the literature that the light source spectrum does not play a significant role in causing disability glare. But caution must be taken that the non-significance found in this study was also likely ascribed to the similar chromaticities or percent transmittance of the two windshields. Future study is needed to clarify this by incorporating windshields with higher transmittance into comparison.

3.4. Glare detection

In this test, the rotation angle of the headlamp was recorded at two moments. One was when the subject began to perceive the glare, and the other was when s/he could not tolerate the glare. For the first moment, a small recorded rotation angle meant high sensitivity to the glare light. As for the other moment, a large recorded rotation angle indicated long endurance to the glare light. The results showed that the age effects were statistically significant in both moments ($F_{1,69} = 81.6$, $p < 0.0001$; $F_{1,69} = 6.3$, $p = 0.01$, respectively). Specifically, a larger mean rotation angle was found at the first moment for the older subjects, i.e. 77.3° versus 41.0°, with s.d. = 1.83 and 3.66, respectively, indicating that the older individuals required more illumination than their younger counterparts to feel the glare. On the other hand, a smaller mean rotation angle was found at the second moment for the older subjects, i.e. 106.3° versus 112.6°, with s.d. = 3.87 and 8.25, respectively, indicating that the older people could bare a lesser amount of glare. The results at the first moment can be explained by Hood and Finkelstein (1986) findings that visual sensitivity to light decreases dramatically with age. As for the second moment, the results support that glare effects get worse in aging individuals, which is mostly due to the increase of the light scattered with aging (Siew et al., 1981).

As for the windshield effects, however, no significant effects were found in either of the two moments ($F_{1,69} = 0.7$, $p = 0.40$; $F_{1,69} = 0.0$, $p = 0.99$, respectively). Additionally, only in this test were the effects of the two glare levels not significant for the two moments ($F_{1,69} = 0.8$, $p = 0.39$; $F_{1,69} = 0.3$, $p = 0.61$, respectively). A possible explanation is that the glare levels selected in this experiment (i.e. 6 lx vs. 20 lx) were both strong enough to trigger similar glare detection and endurance. Future study is needed to elucidate the possibility by using just noticeable glare levels or different rating scales.

In conclusion, the study showed that alternating between the two tested tinted windshields did not result in a remarkable visual performance change, in terms of visual acuity and glare response, for either age group. Since both of the windshields transmit a great portion of blue color spectrum, we failed to test whether or not blue color spectrum has mixed effects on visual acuity and discomfort glare rating. However, as there was no significant interaction found between the two tinted windshields and the two age groups, the study suggested that in the scope of the tested visual responses, from the visual performance point of view, the automobile designers may utilize either of the two windshields equally for both age groups.

4. Discussion

The present study showed that the two tested tinted windshields performed similarly in terms of drivers' visual acuity and glare response for both age groups. The implications of the results are discussed here along with limitations and future plans.

At the equal visible light transmittance of 75%, the study indicated that driving, especially at nighttime, is not affected by the two windshields (i.e. bluish vs. greenish). The size of the Landolt's circle target used in the contrast threshold test was based on the actual size of the circle for testing visual acuity at 200/20 or 0.1. Such a setup aimed to test one's contrast threshold at lower spatial frequency (the number of lines or features per unit distance), which is of great importance for mesopic or scotopic vision in nighttime driving (Ginsburg, 1986; Miller and Nadler, 1990). The fact that no statistically significant difference of visual performance was found with the two tested windshields indicated that the nighttime vision of a driver would remain unchanged under the two tested tinted windshields. In other words, driving behind one of the windshields would be comparable to driving behind the other in terms of the tested visual responses, i.e. visual acuity and glare response. Although there were only two tinted windshields tested, the two windshields are expected to represent many of the legally tinted windshields in the US market in that many states in the US restrict the color used in tinting automotive glasses, e.g. the color of Red, Amber, and Yellow (International Window Film Association, 2007). Besides, as the study focused on testing the difference in visual performance caused by different tinted windshields, no control group (e.g. testing flat windshields which have transmittance of 80–90% or testing without windshield for 100% transmittance) was included. Therefore, a future study needs to compare windshields with various levels of percent transmittance, including untinted windshields, and more pronounced differences in chromaticity. The difference of visual performance may be found between them due to the less alteration of the spectral contents of glare light by untinted windshields. Additionally, an evaluation of coated glass windshields may also be of value.

On the other hand, the glare levels chosen in this study differed from each other greatly (6 lx vs. 20 lx), which might be one of the reasons why the glare level effects were statistically significant in most of the tests. Compared to the findings of other contemporary investigations, however, the results of the discomfort glare rating test reported here are still within the common range. Theeuwes et al. (2002) reported a relationship between glare illuminance and the classical DeBoer discomfort glare rating scale. Using their formula, the predicted classical DeBoer discomfort glare ratings for the glare illuminance at 6 lx and 20 lx are 3.4 and 2.3, respectively. Since the revised DeBoer discomfort glare rating scale in our study is inversely related to the classical DeBoer discomfort glare rating scale, the corresponding ratings of the predicted values in our scale are 5.6 and 6.7, respectively, which are similar to the mean values of our data (i.e. mean = 5.4 and 6.3; s.d. = 0.24 and 0.25, respectively). Although the subjects were asked to give their ratings while fixating on a dot in both studies, it should be noted that the instructions for the classical DeBoer discomfort glare rating scale and the revised one were different. Specifically, the classical DeBoer rating scale does not have a detailed explanation, compared with the revised DeBoer rating scale (see the "Viewer's reaction" column in Appendix A), of what sensations are actually represented by each number of the scale. As a result, a person may understand the two scales differently, which may cause the failure in the direct comparison of the results by using formula: $9 - X = Y$ (where X is the value in the classical DeBoer rating scale; Y is the value in the revised DeBoer rating scale). Such psychophysical effects associated with the two rating scales will be explored in future research. Additionally, as the classical DeBoer scale has been suggested to be not effective in assessing the discomfort glare feelings (Theeuwes et al., 2002), effort is needed to test the effectiveness of the revised DeBoer scale or to develop new scales to measure discomfort glare.

Lastly, besides the windshield effects, it was interesting to note that no distance effects were found in the visual acuity test for either age group under daytime and nighttime conditions. According to Atsumi (1995) findings, visual distance should play a role in visual acuity in aging population. But it seems to work only within a short range (< 100 cm). Beyond that range, visual acuity appears to remain stable and is influenced mainly by age. As such, it may be unnecessary to incorporate the distance effects into the study of visual acuity for automobile drivers, unless the visual acuity for perceiving dashboard information is of concern, because the visual distance of an object outside a vehicle is usually beyond 100 cm away from the driver.

In summary, this study evaluated the effects of the change of the tinted windshields on drivers' visual acuity and glare response. The results indicated that alternating between the tested bluish and greenish windshields did not lead to noticeable difference in drivers' visual performance, either for older drivers or for younger counterparts. That is, alternating between these two tinted windshields would not pose a problem on drivers' visual performance. As the prevalence of vision problems increases with the advancing of age, future research is needed to evaluate the effects of tinted windshields on people with vision problems, which would be beneficial to the understanding of the relation between windshield tinting and the visual performance of drivers with potential vision problems. Additionally, our study is limited to the two tested windshields. Commercial windshields with distinctly different spectral properties from the tested ones should be investigated so as to conclude that any particular choice of windshields would not affect one's vision significantly. We also expect future study to test the potential difference between tinted windshields, coated windshields, and traditional untinted windshields, which may be of higher visible transmittance, to ensure tinting windshield would not impair human vision. Despite these limitations, however, our study can be viewed as a simple method to test glass effects on drivers' visual performance for not only tinted and untinted windshields but other glasses such as vision glass, including coated glass, and privacy glass as well.

Acknowledgement

This study was supported by a grant from PPG Industries, Inc.

Appendix A. Revised DeBoer discomfort glare rating scale

Discomfort glare is glare that a person finds uncomfortable to a greater or lesser degree. Please rate your level of discomfort glare for the light setting based on the following scale by giving the point that most closely matches your perception of the discomfort glare level (note that response can be placed between numbers).

General description	Precise description	Viewer's reaction
Acceptable	1. Not noticeable	There is no glare with this light setting, and I could look at it for any length of time with no discomfort.
	2. Just noticeable	There is a small amount of glare with this light setting, but I could look at it for a long time without discomfort.
	3. Satisfactory	The level of glare is tolerable for this light setting. I could look at if for a few minutes without discomfort.
Borderline	4. Not quite satisfactory	The level of glare is a little bothersome. I might want to look away in less than a minute.
	5. Just acceptable	The level of glare is at the border of acceptability. I might want to look away in less than a minute.
	6. Bordering on disturbing	The level of glare is somewhat disturbing. I might want to look away in less than 30 s.
Undesirable	7. Disturbing	The level of glare is definitely disturbing. I would want to look away in less than 15 s.
	8. Nearly unbearable	The level of glare is nearly unbearable. I would want to look away within 5 s.
	9. Unbearable	The level of glare is definitely unbearable. I would want to look away in a second or two.

References

Abrahamsson, M., Sjostrand, J., 1986. Impairment of contrast sensitivity function (CSF) as a measure of disability glare. Investigative Ophthalmology and Visual Science 27, 1131.

Atsumi, B., 1995. Development of simulating the visual acuity elder people. Toyota Technical Review 45 (1), 28–33.

Corso, J.F., 1981. Aging Sensory Systems and Perception. Praeger, New York.

Ginsburg, A.P., 1986. Spatial filtering and visual form perception. In: Boff, K.R., Kaufman, L., Thomas, J.P. (Eds.), Handbook of Perception and Human Performance, vol. II. John Wiley and Sons, New York, pp. 34-1–34-41.

Hood, D.C., Finkelstein, M.A., 1986. Sensitivity to light. In: Boff, K.R., Kaufman, L., Thomas, J.P. (Eds.), Handbook of Perception and Human Performance, vol. I. John Wiley and Sons, New York, pp. 5-1–5-66.

International Window Film Association, 2007. State window tinting rules and laws chart. Accessed on 2/18/07 at: <http://www.iwfa.com/iwfa/Consumer_Info/auto_statelaws.html>.

Kerker, M., 1969. The Scattering Light of and Other Electromagnetic Radiation. Academic Press, New York, pp. 30–40.

Lockhart, T.E., Atsumi, B., Ghosh, A., Mekaroonreung, H., Spaulding, J., 2006. Effects of planar and non-planar driver-side mirrors on age-related discomfort glare responses. Safety Science 44, 187–195.

Long, G.M., Garvey, P.M., 1988. The effects of target wavelength on dynamic visual acuity under photopic and scotopic viewing. Human Factors 30, 3–13.

McLaughlin, S., Hankey, J., Green, C.A., Larsen, M., 2004. Discomfort glare ratings of swiveling HID headlamps. SAE Technical Paper Series, 2004-01-2257.

Miller, D., Nadler, D.J. (Eds.), 1990. Glare and Contrast Sensitivity for Clinicians. Springer-Verlag, New York.

Owsley, C., Sloane, M.E., 1990. Vision and aging. In: Bolter, F., Grafman, J. (Eds.), Handbook of Neuropsychology, vol. 4. Elsevier, Amsterdam, The Netherlands.

Paulsson, L.E., Sjostrand, J., 1980. Contrast sensitivity in the presence of glare light. Investigative Ophthalmology and Visual Science 19, 401–406.

Shinar, D., Schieber, F., 1991. Visual requirements for safety and mobility of older drivers. Human Factors 33, 507–519.

Siew, E.L., Opalecky, D., Bettelheim, F.A., 1981. Light scattering of normal human lens. II. Age dependence of light scattering parameters. Experimental Eye Research 33, 603–614.

Sivak, M., Flannagan, M.J., Aoki, M., 1997. Glare and mounting height of high-beam headlamps used as daytime running lamps. Lighting Research and Technology 29 (4), 206–210.

Sivak, M., Flannagan, M.J., Schoettle B., Adachi, G., 2003. Driving with HID headlamps: a review of research findings. SAE Technical Paper Series, 2003-01-0295.

Sivak, M., Flannagan, M.J., Traube, E.C., Sato, T., 1994. Evaluations of in-traffic performance of high-intensity discharge headlamps. Lighting Research and Technology 26 (4), 181–188.

Theeuwes, J., Alferdinck, J.W.A.M., Perel, M., 2002. Relation between glare and driving performance. Human Factors 44, 95–107.

Van Derlofske, J., Bullough, J.D., Dee, P., Chen, J., Akashi, Y., 2004. Headlamp parameters and glare. SAE Technical Paper Series, 2004-01-1280.

Van Derlofske, J., Chen, J., Bullough, J.D., Akashi, Y., 2005. Headlight glare exposure and recovery. SAE Technical Paper Series, 2005-01-1573.

Weymough, F.W., 1928. Visual acuity within the area centralis and its relation to eye movements and fixation. American Journal of Ophthalmology 11, 947.